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Growth and yield of nine pine species in Angola

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Abstract: A species introduction experiment including several tropical pines and eucalypts was established in 1966/1967 in the Tchianga research station in Angolan Highlands. Despite 27 years of political conflict (1975–2002) and lack of management, the research experiment has remained relatively well conserved. We measured the best conserved plots that were 41 years old in 2007 to obtain information on the growth of different pine species. We calculated stand characteristics including basal area, dominant height, mean diameter, and stand volume for *Pinus patula* Schiede ex Schiltdl. Et Cham., *Pinus pseudostrobus* Lindl., *Pinus kesiya* Royle ex Gordon, *Pinus devoniana* Lindl., *Pinus chiapensis* (Martinez) Andresen, *Pinus elliottii* Engelm., *Pinus greggii* Engelm. Ex Parl., *Pinus montezumae* Lamb. and *Pinus oocarpa* Schiede ex Schltdl. The growing stock volume at 41 years was the highest in *P. pseudostrobus*, 1,325 $m^3 \cdot ha^{-1}$, followed by *P. kesiya* with 1,200 $m^3 \cdot ha^{-1}$. The widely planted *P. patula* had a growing stock volume of 892 $m^3 \cdot ha^{-1}$. *P. oocarpa* and *P. pseudostrobus* had the highest stand basal area, over 80 $m^2 \cdot ha^{-1}$. Using increment core analyses we studied the temporal development of stand characteristics. Analysis of the mean annual increment (MAI) showed that rotation lengths of 20–30 years would maximize wood production. With these rotation lengths, the MAI of *P. pseudostrobus* would be 35 $m^3 \cdot ha^{-1}$. Other productive species were *P. kesiya, P. oocarpa* and *P. chiapensis*. *P. patula* had a maximum MAI of 20 $m^3 \cdot ha^{-1}$. *P. greggii* had the lowest mean annual volume production, only about 13 $m^3 \cdot ha^{-1}$.

Keywords: *Pinus chiapensis*; *Pinus devoniana*; *Pinus elliottii*; *Pinus greggii*; *Pinus kesiya*; *Pinus montezumae*; *Pinus oocarpa*; *Pinus patula*; *Pinus pseudostrobus*; species experiment

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Introduction

Angolan forest plantations date back to the early 1930s, with the introduction of *Eucalyptus* spp. as a fuel supply for the Benguela Railway under the Portuguese colonial rule, after the supplies from the native miombo forest collapsed (Silva 1971). Large eucalyptus stands were established along the railway lines. They grew well, especially in the Angolan Highland's ferralitic plateau. *Eucalyptus saligna* SM. and *Eucalyptus grandis* Hill ex Maiden were the most productive species with annual growth rates close to 40 $m^3 \cdot ha^{-1}$ (FAO 1998).

Since the 1950s the interest in pulp production increased as the national and international paper market needed new sources of raw material (Silva 1971). New plantations of mainly *E. saligna* but also *Pinus patula* Schiede ex Schiltdl and *Cupressus lusitanica* Miller were established as a fibre source for the national cellulose mill. Later reforestation projects also included large plantations of *P. patula* for supplying the fast-growing construction industry in the flourishing Angolan economy of the 1970s. The forest sector was one of the fastest growing parts of the economy in the region. The colonial enterprises, namely Caminho de Ferro de Benguela (CFB) and Companhia de Celulose do Ultramar Portugues (CCUP), planted more than 100,000 ha of exotic tree species. At the time of independence in 1975 forest plantations in the Angolan Highlands covered 140,000 ha, 40,000 ha of which were *P. patula* (FAO 2003). Currently, the eastern and southern African forest sectors are increasing the area of planted exotic tropical pines. For example, more than 100,000 ha of *P. patula* and 45,000 ha of *Pinus elliottii* Engelm. were planted during the past five years in southern Africa (FAO 2006).

The development of the forest sector activated silvicultural studies in the Tchianga Research Station. During the 1960s, it was the only academic agrarian institution in the country. Technicians and scientists from Portugal established experimental plots in the region, including species introduction trials. Trials were set up in the Cuima plantation area, Saccala perimeter and Tchianga University campus. The tested species included *Eucalyptus*, tropical *Pinus,* and *Cupressus* species. They were tested

during the 1960s and 1970s also in other Southern African countries, especially South Africa and Zimbabwe, where the seeds used in the Angolan trials were imported.

Following the independence of 1975, 27 years of civil war ensued. During this period, extensive illegal logging was common in the forests close to the main cities due to the lack of any other fuel source. Uncontrolled cuttings rather affected the forests except for the forest in Tchianga campus, where remained the only place with preserved experiments. However, the Tchianga experiment was affected by fires. In July 2005, a fire initially designed for cleaning the nearby agriculture plots, became uncontrollable and destroyed some of the plots. Recurrent uncontrolled fires continue to destroy forest stands including plantations and species introduction plots putting the permanence of the few remaining research plots at risk. Consequently, the probability of losing this unique experiment is high, which would result in the disappearance of the information contained in the trees and plots.

There are only a few scientific articles about pine growth in Angola. Guerreiro (1973) and Melo (1974) studied the growth of *P. patula*. Fonseca and Louzada (1986) analyzed the chemical and physical properties of pine wood in the Angolan Highlands. Some technical reports were also produced (Sampaio 1966; Silva 1971). Therefore, analysis of the growth of the plots in the Tchianga research station would provide a valuable benchmark reference on the performance of several pine species in Angola.

Some studies on the species tested in the Angolan Highlands have been carried out elsewhere to determine their growth potential when planted as exotics in southern and eastern Africa. Several pine species have been studied in southern Africa (Poyton 1979), such as *Pinus kesiya* Royle ex Gordon and *Pinus oocarpa* Schiede ex Schltdl. in the Highlands of Tanzania (Saramäki 1992), *P. kesiya* and *P. patula* in Zambia and Zimbabwe (Pukkala and Eerikäinen 1999, 2000; Eerikäinen 2003) and Tanzania (Mugasha et al. 1996; DFSC 2003), and *P. oocarpa* in Kenya (Changala and Gibson 1984).

Similar tests have been carried out in South and Central America. Verzino et al. (1999) developed basal area growth curves for *P. patula* plantations in the Argentinean central province of Cordoba for comparing its performance with other species. In Brazil, *P. oocarpa* provenances were tested for cerrado plantations (Moura et al. 1998), and Wright et al. (1996) tested *Pinus chiapensis* (Martinez) Andresen in Colombia. Dvorak et al. (1996) evaluated the performance of *Pinus greggii* Engelm. Ex Parl. in South Africa, Colombia and Brazil, while Viveros-Viveros et al. (2007) studied the growth and frost resistance of *Pinus pseudostrobus* Lindl. and *Pinus montezumae* Lamb. in the state of Michoacan (Mexico).

With the exception of *P. kesiya*, the tested species originate from the highland regions of Central America, from Honduras to the Mexican Sierra Madre ranges. They grow at altitudes from 600 to 3,500 m, where the annual precipitation is between 650 and 3,000 mm, and temperatures range between 12ºC and 28ºC (Pukkala 2000). *P. kesiya* originates from the mountain ranges in South East Asia from Assam and Burma through Vietnam to the Philippines (Mugasha et al. 1996). The tested species have different frost tolerances with *P. kesiya* and *P. pseudostrobus* being frost sensitive and *P. patula*, *P. elliotti* and *P. greggii* being more frost tolerant (Dvorak et al. 1996, 2000; DFSC 2003; Farjon 2005).

The purpose of the present research was to produce information from the Tchianga pine experiment before it disappears. The study reports the growth performance of nine pine species in the Central Highlands of Angola. The current yield was calculated and the temporal development of stand characteristics was examined. We report the basal area, mean diameter and growing stock volume at 41 years, as well as the temporal development of stand volume, basal area and mean diameter. Mean and current annual volume increments were also analysed.

Material and methods

Description of the region

Tchianga, which hosted the species introduction experiment, is located in the Central Highland region of Angola (Fig. 1). The area is a uniform plateau of approximately 7.9 million ha. Elevation ranges from 1,500 to 1,800 m (Marcelino 1985; Diniz 1998). According to the Köppen classification system, the area corresponds to climate class Cwb (temperate with cold winter and hot summer). There is a rainy season from October to April coinciding with the hottest period and having a total precipitation of 1,100–1,400 mm, and a dry and cold season with almost no rain from June to August. The remaining months, May and September, present transitional characteristics. The wettest month is December, while a two- to three-week dry period frequently takes place mainly in January. The mean annual temperature is 20ºC, with mean monthly maximum of 27ºC and minimum of 11ºC. In some areas the temperature can fall to 0ºC (MIIA 1971; Diniz 1998).

The Highlands' soils are commonly Oxisols (USDA taxonomy), accounting for more than a third of the soils in Huambo province (MPA 1961). The soils are acid with pH between 5.5 and 6.5, and they have a low nutrient content with the exception of the hydromorphic soils in the alluvional valleys and some paraferralitics where the nutrient content and pH are higher (Diniz 1998).

The dominant vegetation types are tropical open grassland and savannah, with patches of open woodland of miombo type (Isorberlina-Brachystegia-Combretum woodland) (Gossweiler 1939). The annual wood production is between 2.5 and 5 $m^3 \cdot ha^{-1}$ with a growing stock volume of 50 to 100 $m^3 \cdot ha^{-1}$ (FAO 1996).

Measurements

The experiment is located in the Tchianga research station (12º43´ S, 15º48´ E), 8 km away from Huambo city, at an altitude of 1,650 m, on a typical flat Oxisol soil, where the annual precipitation is 1,400 mm. The Tchianga species introduction experiment was set up in 1966 including 22 *Eucalyptus* species and 14 *Pinus* species, of unknown proveniences. The experiment

is divided into three blocks with two repetitions for the main species. The experiment also includes three larger stands where *P. patula, P. kesiya, P. oocarpa* and *P. elliotii* were planted for silvicultural research. No treatments have been done in the plots since planting. However, illegal logging affecting mainly suppressed and dead trees has taken place since 1994. The logging intensity was the highest during 1994–2000. Table 1 contains some information on illegal logging during 1994–2007. The estimates are based on the stumps present in 2007.

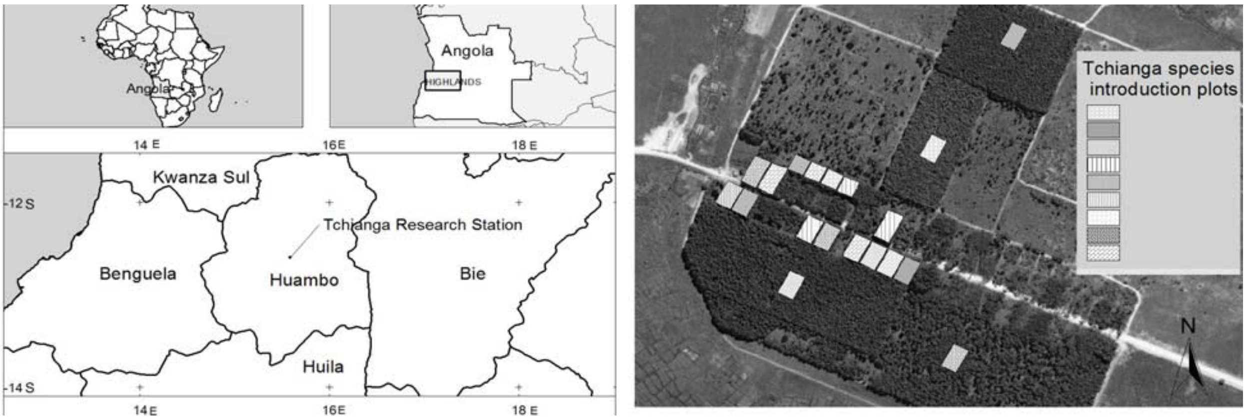

Fig. 1 Location of the Tchianga species introduction experiment in Central Angolan Highlands. The analysed sample plots of the nine pine species are shown (image obtained from Google Earth).

Table 1. Information about the sample plots used in the analyses.

Species	No. of plots in mean height modelling	No. of plots in yield analysis	Height multiplier X_i in Eq. 3	Mean height (m)	Illegal logging[a] (trees·ha^{-1})	Illegal logging rate[a] (trees ha^{-1} year^{-1})	No. of survivors ha^{-1}	Total thinning rate[b] (% year^{-1})
P. patula	8	3	1.064	33.2	179	14	727	2.5
P. pseudostrobus	3	3	1.089	32.9	152	12	923	1.9
P. kesiya	3	3	1.151	34.7	80	6	851	2.3
P. devoniana	1	1	0.995	30.1	190	15	819	2.2
P. chiapensis	1	1	1.02	30.8	114	9	1048	1.6
P. elliottii	2	2	0.911	27.5	171	13	791	2.3
P. greggii	3	3	0.805	24.4	399	31	703	2.6
P. montezumae	1	1	0.972	29.3	210	16	724	2.5
P. oocarpa	2	2	0.866	25.9	80	6	1143	1.4

[a] Illegal logging estimates are for 1994–2007; [b] Includes self-thinning and Illegal logging

Fifteen plots were measured in the species introduction experiment. The selected plots included only those *Pinus* species that had at least 700 survivors ha^{-1} in 2007 and were not significantly damaged in recent fires. In order to increase the number of repetitions, four additional plots were measured in the larger stands that surrounded the experiment. The experiment established in 1966 includes 27 plots and 14 pines species. However, only 19 plots and 9 species were preserved well enough and included in this study (Fig. 1).

The plot size, excluding two border lines on each side, was from 756.25 m^2 (27.5 m × 27.5 m) to 1031.25 m^2 (27.5 m × 37.5 m), and stand density ranged from 703 to 1,143 trees·ha^{-1}. Diameter at breast height (dbh) was measured on each tree, while height and bark thickness were measured on 12 trees per plot covering the whole range of tree sizes. We took 5-mm thick radial cores from every tree with an increment borer in plots with the highest stand volume. Fifteen cores per plot (approximately 50% of trees) were taken in the other plots.

Once the cores were dried, superficially cleaned and fixed onto wood sheets, they were scanned with a high resolution camera. The scanned images and the Arc GIS ESRI software were used to measure the annual rings creating a radial increment dataset file. Discriminating false rings, identifying the limit of adjacent rings within the large growths of the first years and discerning the small growths of the last years were the main difficulties in the measurements. The dataset included 18,245 radial increment measurements. That means that 57% of all radial increments were measured (41 years x 779 trees).

Data analysis

A plot-wise model was fitted for the current tree height (h, m) using the measured diameters and heights of the height sample trees. The model was as follows:

$$h = 1.3 + d^2 / (a_0 + a_1 d)^2 \quad (1)$$

where d is diameter at breast height over bark.

These height models were used to calculate the heights of non-sampled trees. Then, the mean height of all trees was calculated. In order to present the results in terms of volume and volume growth, the stand volume was calculated using the following equation:

$$V=FGH \quad (2)$$

where, F is the form factor, G is stand basal area (m^2ha^{-1}), and H is the mean tree height (m). The form factor was taken as 0.5, which is commonly used for tropical pine species growing in southern and eastern Africa (Hansen et al. 2003; Mugasha et al. 2004).

Since the mean height was required also for the past years, to calculate past stand volumes from Equation 2, a model was fitted for the temporal development of mean tree height:

$$H_i = X_i\, T^2/(0.934+0.159T)^2 \quad (3)$$

where H_i is the mean height of species i at age T, and X_i is a multiplier showing the ratio between the measured mean height of species i at age T and the curve $T^2/(0.934+0.159T)^2$ (Table 1). The model is based on all measured 41-year-old plots and five additional plots measured in younger *P. patula* stands, which were 10 (2 plots) or 34 (3 plots) years old plantations.

A species-specific model was fitted between single bark thickness (bark, mm) and diameter (d, cm). This model was used to calculate the bark thickness of all the trees. The bark model was as follows:

$$Bark = a_0 + a_1 d \quad (4)$$

where *Bark* is single bark thickness (cm) and d is the diameter at breast height (cm). In the calculations it was assumed that the $(d-2\times Bark)/d$ ratio (underbark/overbark diameter, henceforth referred to as u/o ratio) has been constant for the whole life of the tree.

Knowing the initial planting density N_0 and the remaining number of trees N_T, it was possible to calculate the average thinning rate for each species (Table 1). Assuming that the annual rate is constant, the number of survivors in year T (N_T) can be computed from

$$N_T = N_0^{\ -kT} \quad (5)$$

Parameter k, the mean annual thinning rate (self-thinning and illegal logging), was calculated from N_0, N_T and T as follows

$$k = (\ln(N_0) - \ln(N_T))/T \quad (6)$$

Stand development was back-tracked to reconstruct the growth history of each tree and plot. This required information on each year's growth for every tree in the stand. Since there were missing radial growth measurements, a linear model was fitted separately for each year and plot, in order to predict the widths of those annual rings which were not available as a measurement. The model was as follows:

$$ir_t = a_t + b_t \times d_t \quad (7)$$

where d_t is over-bark breast height diameter at the end of year t (cm), ir_t is the radial growth of the year (cm), and a_t and b_t are model parameters for year t.

The tree and stand characteristics one year ago were calculated as follows: (1) Obtain under-bark diameter by multiplying by over-bark diameter with the u/o ratio; (2) Calculate under-bark diameter one year ago by subtracting the doubled radial growth (measured or predicted) from the under-bark diameter; (3) Get over-bark diameter one year ago by dividing the under-bark diameter by the u/o ratio; (4) Calculate 1-year over-bark diameter increment as the difference between current dbh and dbh one year earlier; (5) Obtain tree age one year ago by subtracting one year from current tree age; and (6) Calculate stand characteristics (basal area, mean diameter, mean height, volume) using tree dimensions one year ago. The same process was repeated until a young sapling stand state was reached.

Results

Growth and yield at 41-year age

There were clear differences between the species in stand volume, basal area and other characteristics (Fig. 2). Generally, *P. pseudostrobus* and *P. kesiya* showed the best growth, especially in volume, diameter and height (Table 1). *P. pseudostrobus* had the highest mean diameter, followed by *P. kesiya*, *Pinus devoniana* Lindl., *P. patula*, *P. oocarpa* and *P. montezumae*. *P. pseudostrobus* and *P. patula* had considerable between-plot variation in diameter.

Based on the current stand volume it is possible to establish three volume classes. *P. pseudostrobus* and *P. kesiya* belonged to the highest volume class, *P. oocarpa*, *P. chiapensis*, *P. patula,* and *P. devoniana* representing the intermediate class, and *P. elliottii*, *P. montezumae,* and *P. greggii* showing the lowest performance. *P. pseudostrobus* had the highest volume in 41 years, 1,325 $m^3 \cdot ha^{-1}$, which is 25 $m^3 \cdot ha^{-1}$ more than that in *P. kesiya* (Fig. 2). When one plot that was affected by illegal loggings was excluded from the data, *P. kesiya* had a similar volume and basal area as *P. pseudostrobus*, 1,362 $m^3 \cdot ha^{-1}$ and 75.5 $m^2 \cdot ha^{-1}$. The stand basal area showed similar trends as volume with the exception that *P. oocarpa* was slightly better than *P. pseudostrobus*. *P. oocarpa* grew well but since its stems were crooked it has no timber uses.

P. oocarpa had the highest number of surviving trees per ha with more than 1,140 trees/ha at 41 years, followed by *P. chiapensis*. *P. montezumae* and *P. greggii* had the lowest number of survivors (Table 1). The mean annual thinning rate was

2.5%–2.6% for *P. patula*, *P. greggii* and *P. montezumae*, 1.4% for *P. oocarpa,* 1.6% for *P. chiapensis* and around 2% for the remaining species (Table 1).

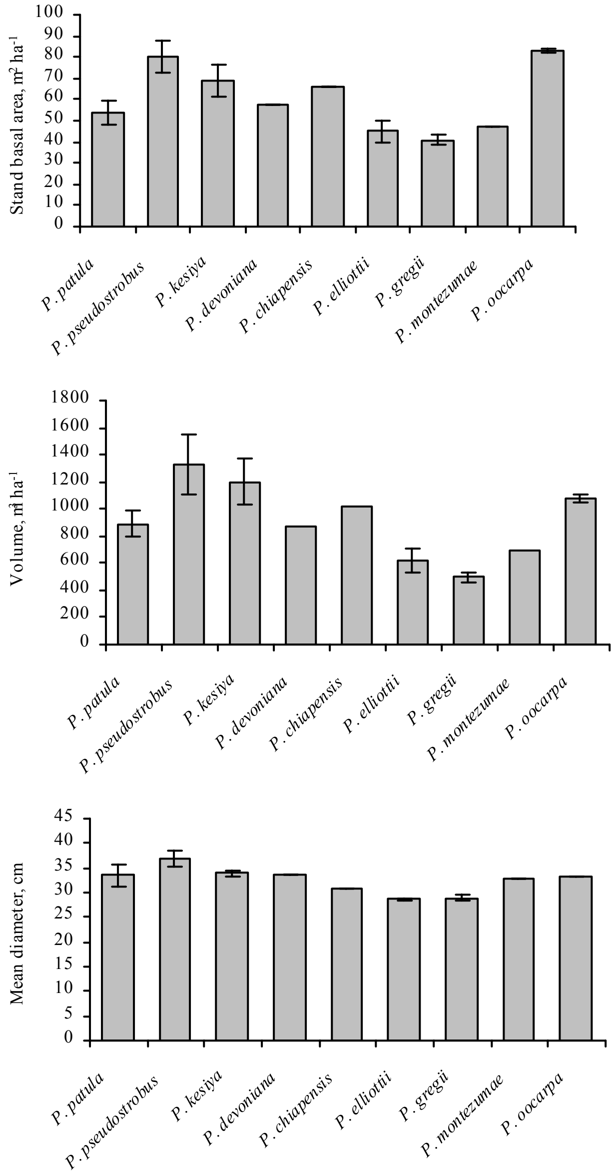

Fig. 2 Stand volume, stand basal area and mean diameter of nine tropical pines at 41 years in the Tchianga experiment. The vertical lines indicate the standard error of mean.

Annual increment

For all species, stand basal area and volume increased faster at young ages, slowing down after 12 to 15 years (Fig. 3). *P. kesiya* and *P. pseudostrobus*, the two fastest growing species, had similar trends in volume development. *P. patula* had a fairly constant volume increment with faster development at young age but it was surpassed by *P. chiapensis* after 12 years. The tested species still showed fast volume growth after 40 years. Similar trends can be seen in basal area with the exception that *P. oocarpa* performed better; it passed *P. kesiya* at 10 years and *P. pseudostrobus* at 35 years.

P. pseudostrobus showed the fastest early growth in mean diameter. Also *P. patula*, *P. kesiya* and *P. oocarpa* grew fast in diameter at young age. The other species had a slower diameter growth during the first decade but at 41 years, *P. devoniana* and *P. montezumae* had reached the mean diameter of *P. patula*.

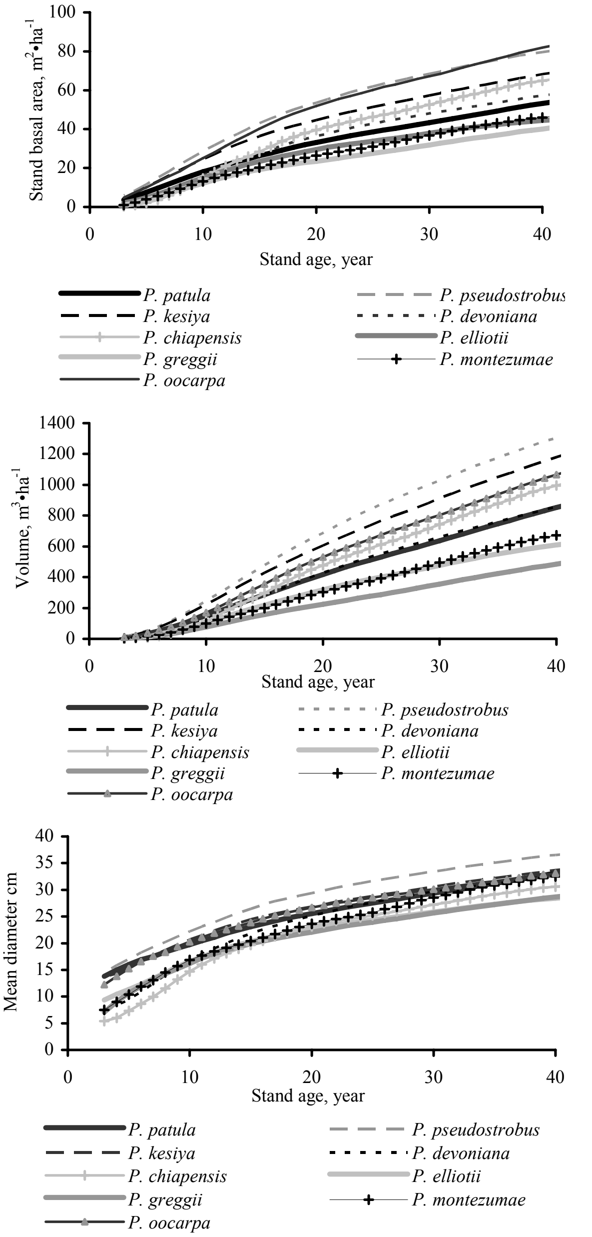

Fig. 3 Volume, basal area and mean diameter development of the analysed tropical pines in the Tchianga experiment.

The mean and current annual increments (Fig. 4) confirmed that the volume increment of *P. pseudostrobus* was faster than in the other species. Its current annual increment (CAI) attained almost 50 $m^3 \cdot ha^{-1} \cdot a^{-1}$ after ten years. This high CAI was maintained for years, declining gradually after 17 years. *P. kesiya*

showed also an early peak in CAI with the maximum a few years earlier than in *P. pseudostrobus*.

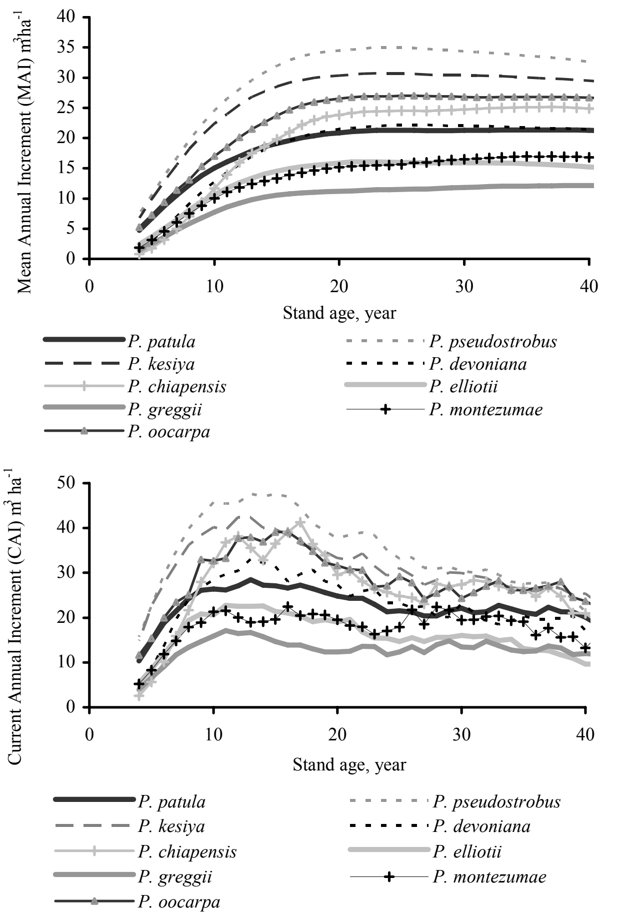

Fig. 4 Mean Annual Increment (MAI) and Current Annual Increment (CAI) of the analysed nine pine species in the Tchianga experiment.

P. pseudostrobus had a maximum MAI of 35 $m^3 \cdot ha^{-1}$ at 20 years, but maintained a high MAI also thereafter. *P. kesiya* showed a similar trend with a maximum MAI of 30 $m^3 \cdot ha^{-1}$ 4 years earlier than in *P. pseudostrobus*. The maximum MAI of *P. patula,* 20 $m^3 \cdot ha^{-1}$, was attained at 16 years. *P. chiapensis* started with a rather slow MAI with 23 $m^3 \cdot ha^{-1}$ at 20 years but the MAI continued to increase slowly for the following 20 years.

Discussion

Analysis of the method

The species trial analyzed in this study is located on a site that is representative for 70% of the highland region of Angola (Diniz 1998). Furthermore, the Miombo vegetation type that characterises this region extends from the Angolans Highlands to Tanzania ranges, including large areas in Zimbabwe, Zambia, Mozambique and Congo Basin (Poyton 1979). Therefore, the results can be generalized to a quite large area in southern Africa.

The limitations in the data include small number of plots on only one site, and one to three repetitions per species. The presence of false rings and small annual growth in the latest years in suppressed trees may have created errors in the measurements. However, the large number of measured increments (18,245) reduces the influence of these errors. In addition, since the measurement errors are not systematic, their effect of the reported results is small. The direction of some cores deviated from the horizontal direction. It introduced a small overestimation, which however was minimised since the radial increments were measured in a direction perpendicular to the boundary between adjacent annual rings. Mortality and illegal logging were ignored when stand characteristics were back-tracked. However, this should not affect the results very much since mortality and illegal logging mainly removed the most suppressed trees that do not contribute much to stand basal area and volume.

The plots used in the study have never been systematically thinned but gradual illegal loggings have been done in some plots since 1994. Most of the illegal logged trees were suppressed trees or dead standing trees having dry wood and dbh around 15 cm (FAO 2009). The mortality rate diverged from one species to another depending on both competition and illegal logging. It was observed that plots further from the main roads and with smaller diameters suffered more from illegal logging. Since a low logging rate was used as a criterion to select the analyzed species and plots, the impact of illegal logging on the results and conclusions remains small. About half of the thinning during 1994–2007 is accounted for by illegal logging. However, since mainly small and suppressed trees were removed, many of the logged trees would otherwise have died, increasing the share of self-thinning. Therefore, the thinning rates reported in Table 1 may not overestimate very much the average self-thinning rate of different species during the whole 41 period of stand development.

The presented methodology to describe stand development, based on analysing the annual rings, has the advantage of being quick and reasonably straightforward. It proved to be highly convenient for completing information from permanent plots where periodical measurements have not been made. Verzino et al. (1999) used a similar methodology based on Stokes and Smiley (1968) for *P. patula* in central west Argentina. Based on annual growth ring measurements it provides growth information that enables a detailed description of each tree and, therefore, stand development. It can be used in abandoned species introduction plots as shown in the present study. However, the method has some limitations inherent to the annual ring analysis and due to missing temporal information on mortality.

The volume growths were calculated using a form factor, stand basal area, and mean stand height. Volume was calculated to facilitate the comparison of our results with previous studies. The form factor used, 0.5, follows the experiences from Malimbwi and Philip (1999) and Mugasha et al. (2004) working with *P. patula* plantations in miombo woodland in Tanzania. The same form factor was used in Hansen et al. (2003) for *P. kesiya* in Zimbabwe, Machado et al. (2005) for *P. oocarpa,* and Drescher et al. (2001) for *P. elliottii* in Brazilian plantations.

Analysis of the results

The species planted as exotics in Tchianga showed volume growth rates substantially higher than in their natural ranges. These results are consistent with international literature (Table 2).

The traditional assumption in southern Africa is that *P. patula* has the highest volume growth (Melo 1974). However, in this study in Angola, four species, namely *P. pseudostrobus*, *P. kesiya*, *P. oocarpa* and *P.chiapensis*, clearly outperformed *P. patula* in volume production. Regarding mean diameter and basal area, our results were mostly within the ranges reported in international literature. *P. patula* and *P. elliottii* in Angola were in the middle or near the lower limit of these intervals. On the other hand, the fastest growing species in Tchianga plots, namely *P. pseudostrobus*, *P. kesiya, P. chiapensis, P. oocarpa,* and *P. patula*, show growth levels similar to the highest values found in literature (Table 2)

Table 2 Growth and yields key indicators in the international scientific literature

Species	Volume growth rate, $m^3\ ha^{-1}a^{-1}$				Mean diameter at 20 years, cm		Basal area at 20 years, $m^2\ ha^{-1}$		Rotation length, y	
	Angola/ This study	*Central America/* Dvorak et al. 1996, Dvorak 2003	*Southern Africa/* Dvorak et al. 1996, Dvorak 2003	*World/*Pancel 1993, Varmola and Del Lungo 2003	*Angola/* This study	*East Africa/* Mugasha et al. 1996	*Angola/* This study	*East Africa/* Mugasha et al. 1996	*World/*Varmola and Del Lungo 2003	*World/*Pandey and Ball 1998
P. patula	20	8	-	11–30	25	-	40	-	31	11–35
P. oocarpa	26	3–4	10–18	10–32	26	26	68	80	23	18–25
P. chiapensis	23	1–2	25	-	21	-	50	-	-	-
P. elliottii	16	-	-	10–20	26	27–29	35	81–97.5	31	11–35
P. kesiya	30	-	-	11–21	26	-	53	-	20	15–18
P. pseudostrobus	35	-	-	15–30	30	-	69	-	-	-
P. greggii	11	3	6	-	20	-	29	-	-	-
P. montezumae	14	-	-	-	22	-	33	-	-	-
P. devoniana	20	-	-	-	24	-	43	-	-	-

Mugasha et al. (1996) reported a mean diameter from 27 to 29 cm and basal areas from 81 to 97.5 $m^2 \cdot ha^{-1}$ for nearly 20 year old unthinned *P. kesiya* stands in a provenance experiment in the Tanzanian Highlands. These results are higher than the ones in Tchianga where the stand basal area at 20 years was 44.7 $m^2 \cdot ha^{-1}$. The mean diameter at 20 years was nearly the same. In the Tanzanian experiment the mean survival rate was close to 90% which is much more than the 50% in Tchianga at 41 years and could explain the reported differences. Mugasha et al. (1996) report that *P. oocarpa* had a mean dbh of 26 cm and a mean basal area of 80 $m^2 \cdot ha^{-1}$ at 16 years, which indicate better growth than in the Tchianga experiment in Angola.

Farjon (2005) described *P. oocarpa* as forming long, often tortuous branches that can join with twisted stems, which is a similar growth pattern as observed in Tchianga. Another feature of *P. oocarpa* was slow initial growth. Competition with grass may explain the low growth rates in early years in our plots, a point also raised by Dvorak (2002). Moura et al. (1998) reported a similar slow initial growth of *P. oocarpa* in Brazilian experiments. A better choice of provenance may have resulted in better quality and faster initial growth.

The usual rotation lengths of *P. patula* plantations in Angola are 25 years (Melo 1974). According to our observations, the MAI of all pine species reached its maximum at 20 years and remained good after that. Therefore, rotation lengths should be 20 years or more. This is within the intervals proposed in literature (Table 2). Our results suggest that 11 years proposed by some authors (Table 2) would be clearly too short for Angola.

Species that had the fastest growth rates are those with the lowest frost resistance. Species less tolerant to frost had higher volume growths than reported in Viveros-Viveros et al. (2007) in the native region of the species in Michoacan, Central Mexico. Viveros-Viveros et al. (2007) found a strong correlation between growth rate and susceptibility to frost damage in *P. pseudostrobus* and *P. devoniana*. The low occurrence of frost events in Tchianga sustained the fast growth of the frost intolerant *P. pseudostrobus* and *P. kesiya*.

Conclusions

The present study shows that species having the lowest frost resistance, namely *P. pseudostrobus*, *P. kesiya*, *P. chiapensis* and *P. devoniana*, grow faster than the commonly planted *P. patula* and *P. elliottii*. Therefore, the results suggest that a change in the species composition of pine plantations may be worthwhile in future projects in Angola and in other miombo vegetation type highlands in southern Africa. It is recommended that the following pine species be considered in future large scale plantations in the Angolan Central Highlands: *P. pseudostrobus, P. kesiya* and *P. chiapensis*. Further studies are, however, required on wood characteristics. For *P. oocarpa*, further testing of provenances having better stem form should be carried out in Angola.

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